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| cetlogo ***CHEMICAL ENGINEERING TRANSACTIONS*** ***VOL. xxx, 2025*** | A publication ofaidiclogo_grande |
| The Italian Associationof Chemical EngineeringOnline at www.cetjournal.it |
| Guest Editors: Bruno Fabiano, Valerio CozzaniCopyright © 2025, AIDIC Servizi S.r.l.**ISBN** 979-12-81206-xx-y; **ISSN** 2283-9216 |

The Indirect Risk of Wind Turbines to Seveso Establishments

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Currently, climate change and renewable energy are hot topics. Therefore, wind turbines are rapidly increasing in number. However, the government, the wind turbine sector and the safety experts must ask the question “Is it safe to install a wind turbine? Is it acceptable to do so at a certain location?”, especially near Seveso establishments, which contain many dangerous substances. What if the wind turbine fails? What if a wind turbine blade is thrown away? What if the wind turbine tower or the nacelle fails? What happens then to the surrounding Seveso establishments, and the installations with dangerous substances? And what happens to the people in the vicinity? In other words, what is the risk posed by the wind turbine to its surroundings? These are questions that need to be answered before the government can grant the wind turbine permit.

In Flanders, guidelines to calculate and assess the risk of wind turbines are published in collaboration with the wind turbine manufacturers and the Flemish certified experts in the context of the Seveso Directive (OMG, 2019b). A distinction is made between the direct and the indirect risk posed by the wind turbine. For the direct risk, the method of The Netherlands (DNV GL, 2014) was mainly followed, with a few adjustments. For the indirect risk, the government of Flanders developed a method in collaboration with the Flemish experts, as The Netherlands or any other country do not have an elaborated method for this. The latter is the focus point for this article.

* 1. Introduction

More wind turbines are being installed due to climate change and the increasing demand for renewable energy. Legislation in Flanders stipulates that an environmental permit must be requested for wind turbines with electrical power above 300 kW. Before granting the permit, a safety study must be drawn up and added to the application, as the government wants to ensure that the risk posed by the wind turbine is acceptable. The safety study must demonstrate that the wind turbine meets the risk criteria regarding the risk posed by the wind turbine, in accordance with the Framework for Wind Turbines accepted by the government of Flanders.

The risk posed by a wind turbine consists of direct and indirect risks. The direct risk is based on the intrinsic failure of a wind turbine, where people in the vicinity are directly affected by a wind turbine fragment. The indirect risk considers the risk to people in the vicinity due to the failure of an installation with dangerous substances that was first hit by a wind turbine fragment. People are therefore not directly, but indirectly affected by the failure of the wind turbine.

The method developed by Flanders for assessing direct and indirect risks is published in the Flemish Wind Turbines Manual (OMG, 2019b) and aligns with the European guideline for assessing the risks posed by wind turbine to the public (IEC, 2023). This article focuses on the indirect risk to Seveso establishments, as this can represents a new development in the risk analysis of wind turbines.

* 1. Failure modes, failure frequencies and effect distances

To calculate the direct or indirect risk of a wind turbine, the failure modes, failure frequencies and effect distances must be identified. Data and formulas were primarily extracted from DNV GL (2014) and adjusted where necessary following Protec Engineering and SGS (2015), SGS (2007) and own insights.

* + 1. Failure modes and failure frequencies

To calculate the risk of a wind turbine, generic failure modes and corresponding failure frequencies (see Table 1) must be used. The following failure modes are considered by default: blade breakage, tower breakage and nacelle breakage.

For blade breakage, it is assumed that the blade breaks off entirely. A distinction is made between blade breakage at nominal speed and blade breakage at overspeed, the latter being 2 x nominal speed. The direction in which the blade is thrown is assumed to be uniformly distributed.

For tower breakage, it is assumed that the tower breaks at a certain point and rotates around this point. The direction in which the tower falls is uniformly distributed. The assumed specific failure mode and failure frequency are dependent on the type of the tower, i.e., steel tower, concrete tower or hybrid tower.

* For a steel tower, following failure modes are applied: (1) tower breakage at the base of the tower with a failure frequency of 1.5E-05/y; (2) tower breakage above ground level in the lower half of the tower with a failure frequency of 3.5E-05/y which is uniformly distributed across half the height; (3) tower breakage in the top half of the tower with a failure frequency of 0.8E-05/y which is uniformly distributed over the top half.
* For a concrete tower, a default failure frequency of 3.5E-05/y is suggested. The failure frequency is uniformly distributed across the full height of the concrete section.
* For a hybrid tower, for the lower concrete tower section, a default failure frequency of 3.5E-05/y is suggested. The failure frequency is uniformly distributed across the full height of the concrete section. For the upper steel tower section, the following failure modes are assumed: (1) tower breakage at the base of the steel section with a failure frequency of 1.5E-05/y; (2) tower breakage above the base of the steel section with a failure frequency of 0.8E-05/y which is uniformly distributed over the steel section.

For nacelle breakage, it is assumed that the nacelle and the rotor come down as a whole and that they fall down in such a way that the rotor surface is in a horizontal plane. The direction in which the nacelle falls is evenly distributed.

* + 1. Effect distances and zones

In Flanders, a distinction is made between the effect distances for (1) the center of gravity of the blade and for (2) the tip of the blade. Refer to Table 1 for the different effect distances from the central axis of the tower, in which the maximum throwing distance is defined as the distance where the center of gravity of the blade ends up after being thrown away; the tip height is defined as the sum of the axis height and half the rotor diameter; and half the rotor diameter is equal to the blade length. The corresponding effect zones are the areas within a circle centered at the central axis of the tower with a radius equal to the effect distance.

*Table 1: Generic failure modes, generic failure frequencies and maximum effect distances of wind turbines*

|  |  |  |  |
| --- | --- | --- | --- |
| Failure mode | Failure frequency[/wind turbine year] | Maximum effect distance for the center of gravity of the blade  | Maximum effect distance for the tip of the blade |
| Blade breakageNominal speedOverspeed | 6.2E-045.0E-06 | Maximum throwing distance | Sum of the maximum throwing distance and the distance from the center of gravity of the blade to the tip of the blade |
| Tower breakage | 5.8E-05 | Sum of the axis height and the distance to the center of gravity of the blade | Tip height |
| Nacelle breakage | 1.8E-05 | Distance to the center of gravity of the blade | Half the rotor diameter |

* 1. Direct risk versus indirect risk for Seveso establishments

This article describes the calculation and assessment of the indirect risks of a wind turbine to Seveso establishments, which store or process dangerous substances and pose a substantial risk to the environment. If an installation at the Seveso establishment containing a dangerous substance fails, it can lead to toxic or flammable clouds, resulting in intoxication, combustion or explosion, potentially causing fatalities.

If the failure of the installation is due to some internal cause, the risk is called the direct risk of the Seveso establishment. But an installation with dangerous substances can also be hit by a part of a failing wind turbine if the installation is within the effect zone of the failing part of the wind turbine. So, the failure frequency of the installation increases by the presence of a wind turbine in the vicinity. And this additional failure can also result in the release of the substance and lead to the death of people in the vicinity of the Seveso establishment. This is called the indirect risk of the wind turbine for the Seveso establishment.

In Flanders, the risk of the establishment is calculated using a QRA (Quantitative Risk Analysis) and the risk image should meet the risk criteria for Seveso establishments, whether or not there is a wind turbine in the vicinity.

* 1. Method for indirect risk

The method for determining the indirect risk of a wind turbine to an installation with dangerous substances involves the following steps: (1) inventory of possibly affected installations, (2) determining the failure mode of the installation, (3) optionally determining the significance of the indirect risk, (4) recalculating the total risk of the establishment, and (5) risk assessment.

* + 1. Inventory of possibly affected installations with dangerous substances

In the first step, it is checked which installations with dangerous substances can be affected by a wind turbine. The starting point are all installations on the establishment within an effect zone of the wind turbine. Underground atmospheric tanks, heat exchangers, pumps, compressors, loading arms, flexibles and the scenario of release of toxic flue gases by warehouse fire can be excluded in advance, if not relevant for external safety. However, in specific situations, e.g. the storage of water-reactive substances or ammonium nitrate at warehouses, a risk analysis can be necessary.

Any aboveground installation, including pipes, which is within an effect zone from the wind turbine is further investigated. Each failure mode of the wind turbine is studied. For each failure mode, a distinction is made between, on the one hand, the location of the installation within the effect zone for the center of gravity of the blade and, on the other hand, the location of the installation outside the effect zone for the center of gravity of the blade and within the effect zone for the tip of the blade.

All underground pressure tanks, including mounded pressure tanks, which are within the effect zone for the center of gravity of the blade for tower breakage or nacelle breakage will be investigated.

For underground pipes, a conservative separation distance is used (Protec Engineering & SGS, 2015). This separation distance is based on the vibrations caused by the impact of the mast and the nacelle on the ground, and which can be propagated in the ground. The determination of the damage caused by ground vibrations is based on the method of (Fernandez C., et al., 2012), who derived an expression for the peak particle velocity at the level of an underground pipe caused by the impact of a fragment on the ground.

* + 1. Determining the failure mode

For each inventoried installation with dangerous substances and for each relevant failure mode of the wind turbine, it is investigated how the installation can fail. The definitions of the installations, the failure modes and how they must be modeled are included in the Risk Calculations Manual (OMG, 2019a).

Aboveground installations

Aboveground installations are assumed to fail if hit. Table 2 shows the type of failure for each type of installation, recorded after consultation with the Flemish certified experts. In this table, a distinction is made between failure modes causing “major damage” to the installation and failure modes causing “minor damage” to the installation. “Major damage” is assumed if the installation is hit by the nacelle, the tower or the center of gravity of the blade. “Minor damage” is assumed when there is indirect impact of the blade, i.e., if the blade hits the installation without the blade's center of gravity hitting the installation. In the calculation of the indirect risk, the consequence “minor damage” should not be included if the consequence “major damage” is possible due to a corresponding failure mode.

Table 2: Failure modes for aboveground installations hit by a wind turbine

|  |  |  |
| --- | --- | --- |
| Installation  | Failure mode in case of “major damage” | Failure mode in case of “minor damage” |
| Atmospheric single containment tanks  | RuptureFull release in 10 minutes | Medium leak |
| Atmospheric tank trucks, railway wagons and tank containers | RuptureFull release in 10 minutes | Medium leak |
| Atmospheric Process installations | RuptureFull release in 10 minutes | Medium leak |
| Double and full containment tanks with metal secondary holder | Rupture of the entire tank system, releasing 100% of its contentsRelease in 10 min of the entire tank system, releasing 100% of the content | No failure mode |
| Double and full containment tanks with concrete secondary holder | Rupture of the entire tank system, releasing 10% of its contentsRelease in 10 min of the entire tank system, releasing 10% of the content | No failure mode |
| Storage tank under pressure | RuptureFull release in 10 minutes | Medium leak |
| Tank trucks, railway wagons and tank containers under pressure | RuptureFull release in 10 minutes | Medium leak |
| Process installations under pressure | RuptureFull release in 10 minutes | Medium leak |
| Pressure drums, tubes | Rupture  | Leak  |
| Cylinders | Rupture  | Rupture  |
| Bundle of cylinders, bundle of tubes | Rupture of 1 cylinder or tube followed by continuous release of all cylinders or tubes | Rupture of 1 cylinder or tube followed by continuous release of all cylinders or tubes |
| Aboveground pipes | Rupture | Medium leak |
| Open storage areas | 1 piece of general cargo fails | 1 piece of general cargo fails |

In case of tower or nacelle breakage, the failure of the bund and the failure of multiple installations at the same time is considered, if it is within the effect zone for the center of gravity of the blade. Also, for installations within a building, protection by the building can be considered.

Underground installations

Underground installations are assumed to fail if they can be hit by the wind turbine. For underground pressure tanks, a medium leak is assumed as failure mode due to both tower and nacelle breakage. Blade breakage is not considered.

Underground pipes

For underground pipes, damage distances for rupture and leak are calculated based on the vibrations caused by the tower and/or nacelle. Formulas can be found in the Wind Turbines Manual (OMG, 2019b) and are based on (Protec Engineering & SGS, 2015).

* + 1. Determining the significance of the indirect risk

For each of the inventoried installations with dangerous substances and per relevant failure mode of the wind turbine, the significance of the indirect risk because of the failure of the wind turbine can be examined as an optional step. You can also immediately proceed to calculating the indirect risk and recalculating the total risk of the establishment.

Determining the significance of the indirect risk can be done (1) by comparing the hit and intrinsic failure frequencies, (2) by performing a consequences analysis and/or (3) by comparing risk images. The choice which approach to follow and/or in which order is free. However, the failure frequency approach can not be applied if failure of the bund or failure of several installations at the same time is to be considered, because of the fact that there are no intrinsic failure frequencies for these scenarios.

Failure frequency approach

In the failure frequency approach, the hit frequency is compared to the intrinsic failure frequency of the installation.

To calculate the hit frequency of the installation by the wind turbine, formulas are described in the Wind Turbines Manual (OMG, 2019b). If the installation can be hit by several wind turbines, the hit frequency is summed for all wind turbines that can hit the installation. The hit frequency is also summed for all failure modes of the wind turbine that cause the same failure mode to be considered at the installation. For example, if blade breakage and tower breakage can lead to a medium leak, then the hit frequency for blade breakage and tower breakage is added.

The intrinsic failure frequency of the installation with dangerous substances is equal to the generic failure frequency associated with the failure mode of the installation to be considered, as indicated in Table 2. These generic failure frequencies are included in Risk Calculations Manual (OMG, 2019a). If several failure modes must be considered for the installation (e.g. rupture and 10 min release), the failure frequencies for the different failure modes are summed. If failure frequency reduction was applied for the installation in the most recent approved safety document of the establishment, the intrinsic failure frequency is the reduced failure frequency and not the generic failure frequency. Failure frequency increase for the installation with dangerous substances is not considered.

If the hit frequency for the installation is less than 10% of the intrinsic failure frequency of the installation, then the indirect risk is not considered significant. If the hit frequency for the installation is 10 % or more of its intrinsic failure frequency, then the indirect risk is considered relevant under the failure frequency approach. This risk is further investigated by either implementing the consequences approach, the risk approach or by recalculating the total risk image of the establishment.

This 10%-rule should be used with caution, considering the current risk assessments of the establishment. For example, if the establishment already has a substantial risk or already applies failure frequency reduction, this rule is not sufficient, and the situation must be examined in more detail.

Consequences approach

The consequences approach considers the consequences resulting from the damage caused to the installation with dangerous substances. The maximum 1% lethality distance is determined for every possible failure mode of the installation because of the failure of the wind turbine.

If the maximum 1% lethality distance of the installation does not exceed the site boundary for any of the possible failure modes, the indirect risk due to the wind turbine is negligible. If the 1% lethality distance does extend beyond the site boundary for at least one of the possible failure modes, then the presence of the wind turbine will affect the QRA of the establishment and there is a relevant indirect risk. In a safety study of a wind turbine, the significance of the indirect risk on the installation will be further investigated. To this end, it is examined whether the 1% lethality zone includes a population considered important, e.g. an area with a residential function, a vulnerable location or a building or area visited by the public (incl. recreation area). If the 1% lethality zone does cover a population considered important, the indirect risk is considered relevant in the context of the consequences approach and is further investigated by either implementing the failure frequency approach or risk approach or by recalculating the total risk image of the establishment. If not, the indirect risk is considered not significant.

Risk approach

The risk approach can be used to determine whether the risk image due to the indirect risk will influence the overall risk image of the establishment. For this, a QRA is performed for the installation possibly hit by the wind turbine, whereby only the scenarios that were identified as relevant are calculated. This QRA is done following the rules of the Risk Calculations Manual (OMG, 2019a), with the exception that the failure frequency that is considered is equal to the hit frequency.

The risk image that is obtained with this is compared with the original risk image of the establishment. If this comparison clearly shows that the wind turbine has no considerable influence on the risk image, it can be decided that the wind turbine can be reconciled with the presence of the installation. If this comparison is not convincing enough, the risk image of the establishment must be recalculated, including the indirect risk.

* + 1. Recalculation of the total risk of the establishment

If earlier steps indicate that the indirect risk is relevant, this will be considered in the QRA of the establishment of which the installation with dangerous substances is part. This is done either (1) by adding the hit frequency to the intrinsic failure frequency of the installation or (2) by inserting an additional scenario in the QRA with the hit frequency. The total risk image of the establishment, direct and indirect risk together, is determined.

* + 1. Risk assessment

To determine the extent to which the presence of the wind turbine can be reconciled with the presence of a Seveso establishment, the overall risk image of the establishment is determined, and it is evaluated whether or not this overall risk image meets the applicable risk criteria (LNE, 2006). This means that the total risk of the Seveso establishment, which consists of the intrinsic direct risk of the Seveso establishment and the indirect risk due to the wind turbine, still meets the criteria for the Seveso establishments, even after pulling up the wind turbine.

* 1. Future developments

The wind turbine industry, along with the associated data and risk assessments, is continuously evolving. Therefore, it is important to stay up to date with the latest developments and adapt the Flemish method where appropriate. For example, in The Netherlands, a new calculation method has recently been developed (Versluis et al., 2024). The intention is to have a good look at the changes in the near future, like the failure modes and the (lower) failure frequencies.

Minor changes with respect to the original method in 2019 have already been made and incorporated in the Dutch version of the manual. A few more minor changes are planned. The English version of the manual will be adapted accordingly.

* 1. Conclusion

The government of Flanders has developed a new method to determine the indirect risk of a wind turbine to Seveso establishments. This includes straightforward approaches to determine relevance, and, if relevant, calculates the total risk of the establishment to ensure that the presence of the wind turbine can be reconciled with the presence of a Seveso establishment. This allows the government to make an informed decision on the requested environmental permit and the Seveso establishment is protected against too risky wind turbines in the vicinity.

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